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ON THE F_2-REGION OF THE IONOSPHERE

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ABSTRACT. Calculations of the total electron production rate in a column of unit cross-section extending from the "bottom" to the maximum electron density height and of the mean production rates in different parts of the F_2-region are made with the help of the attachment coefficient model suggested by Ratcliffe *et al.* (1956). It is found that the results are consistent with those expected from the hypothesis of Bradbury for the formation of the F2-region. The calculations are made by the method suggested by the author (1958).

INTRODUCTION

The diurnal variation of electron density N at a given height in an ionized region, neglecting the effects of movements, is governed by the equation

$$\frac{dN}{dt} = q - KN^{\eta} \qquad \dots \quad (1)$$

where q = electron production rate

K = electron loss coefficient

and $\eta = 1$ or 2 depending on the electron loss process.

In the E and F_1 regions the effects of movements are negligible. For these regions Eq. (1) may be utilised for calculating the production rate from the experimental values of $\frac{dN}{dt}$ and N provided the loss process and the loss coefficient K are known. In the F_2 region, however, movements of the electrons produce changes in electron density at a rate comparable to dN/dt of Eq. (1). Computations of production rate with the help of this equation cannot, therefore, yield reliable values. It is also not possible to take account of the effects of the movements in the computation as little is known about their nature and magnitude. Further, the height of the F_2 region has large diurnal variations and its thickness also changes considerably at times. These difficulties notwithstanding, study of the production rates in different levels of the thick F_2 region, is desirable for testing the theories of the formation of the F_2 region.

A method of computation of such production rates was therefore proposed by the author of this paper. The method consists in dividing a column of unit cross-section of the region extending from the "bottom" to the height of maximum electron density into four sections of equal length. Mean production rate in each of these sections (same as mean production rate in four different parts of the thick F_2 region) is computed from the diurnal variation of the total number of electrons in it. The total production rate in the "unit column" of the F_2 region and the mean production rate in the region are also computed. Such computations obviously minimise the effects of layer movement as a whole, movements of electrons, and layer contractions and dilutions due to thermal changes. There is, of course, the proviso that the fraction of the total number of electrons present in each of the four "unit" sections is not changed. Mean hourly values of N at a series of heights in the F_2 region over Slough for the months of January and March, 1950 on international quiet days were utilised for the computation. "Tables of F_2-layer Electron Density on International Quiet Days" computed by Schmerling and Thomas (1955) were obtained from the Radio Group, Cavendish Laboratory, Cambridge, England. The height variation of the attachment coefficient as suggested by Ratcliffe *et al.* (1956) from night-time observations over Slough, Watheroo and Huancayo, was utilised.

In the paper of the author referred to above (Datta 1958) the diurnal variations of the production rates (as mentioned above) were delineated for the month of January, 1950. In the present paper, computations are made of the same parameters for the month of March of the same year. Values of the mean production rates have also been calculated on the basis of Bradbury's (1938) hypothesis for the formation of the F_2 region These are compared with the results for the two months, January and March, 1950 obtained by the suggested method of analysis.

RESULTS

Fig. 2(a) depicts the diurnal variation of the total number of electrons n in a column of unit cross-section extending from the "bottom" to the height of maximum electron density in the F_2 region over Slough for the month of March, 1950. Fig. 2(b) shows the diurnal variations for the same month of n_r (r = 1, 2, 3, 4), the total number of the electrons in each of the four sections of the column taken in order from the "bottom". Hourly values of the number of electrons and the loss rates in each of the sections were calculated by Simpson's rule for numerical integration. Loss rates were calculated with the help of the height variation of the attachment coefficient as suggested by Ratcliffe *et al.* (1956) and extrapolated to a height of 200 Km. (Fig. 1). To obtain half hourly values of $\left(\frac{dn_r}{dt}\right)$ and n_r a linear change between the hourly values of n_r was assumed. A quassi-equilibrium condition in each of the columns was assumed from 10 hrs. to 14 hrs. Such an assumption is justified in the neighbourhood of the midday when loss rate and production rate are much larger than $\left(\frac{dn_r}{dt}\right)$. The diurnal variations of mean production rate for the month of March,

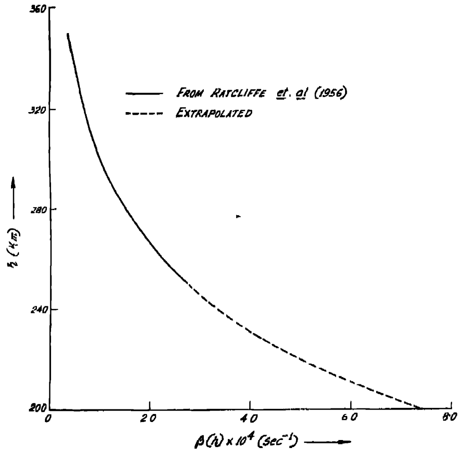

Fig. 1. Height variation of the attachment coefficient suggested by Ratcliffe *et al.* (1956).

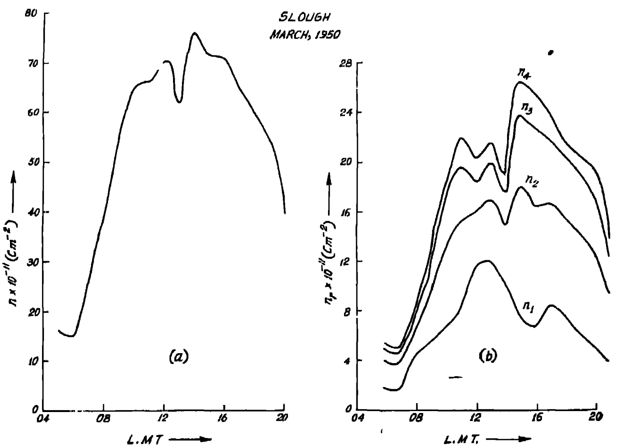

Fig. 2. (a) Diurnal variation of n in the F_2 region for the month of March, 1950.
(b) Diurnal variations of n_r ($r = 1,2,3,4$) in the F_2 region for the month of March, 1950.

1950 over Slough are shown in Fig. 3. The diurnal variation of the mean production rate (q) and the total production rate (Q) in the whole column of unit

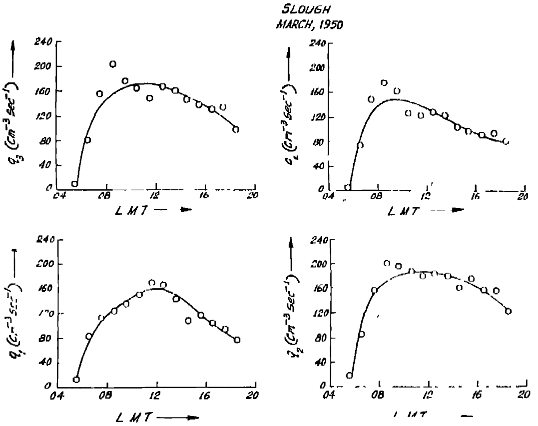

Fig. 3. Diurnal variations of q_r (r = 1,2,3,4,) in the F_2 region for the month of March, 1950.

cross-section extending from the "bottom" to the maximum electron density height in the F_2 region for the months of January and March, 1950 over Slough, are shown by broken lines in Fig. 5 and Fig .6 respectively.

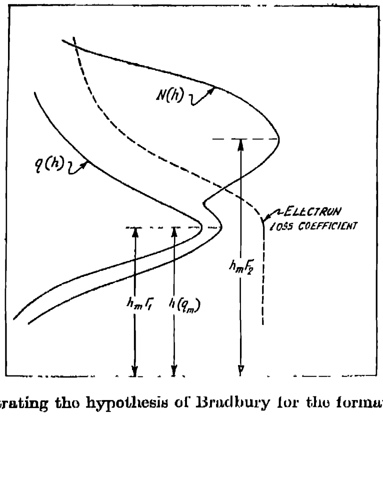

Fig. 4. Diagram illustrating the hypothesis of Bradbury for the formation of the F_2 region.

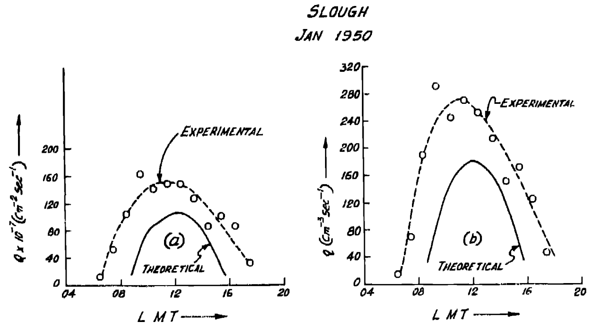

Fig. 5. Diurnal variation of Q and q (Experimental and theoretical) in the F_2 region for the month of January, 1950.

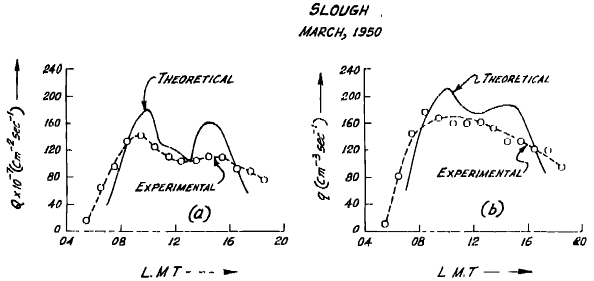

Fig. 6. Diurnal variation of Q and q (experimental and theoretical) in the F_2 region for the month of March, 1950.

TABLE 1

Half hourly values of q_r ($r = 1, 2, 3, 4$), Q and q.

January 1950—Slough

Hour (L.M.T.)	q_1 $cm^{-3}.sec.^{-1}$	q_2 $cm^{-3}.sec.^{-1}$	q_3 $cm^{-3}.sec.^{-1}$	q_4 $cm^{-3}.sec.^{-1}$	$Q\times 10^{-7}$ $cm^{-2}.sec.^{-1}$	q $cm^{-3}.sec.^{-1}$
0630	14	17	16	14	13	15
0730	37	70	84	89	51	70
0830	128	227	200	203	106	190
0930	205	332	314	317	163	292
1030	180	303	273	222	141	245
1130	193	319	306	262	151	270
1230	183	311	283	230	151	252
1330	173	255	231	191	127	213
1430	115	195	166	119	86	149
1530	135	208	190	151	102	171
1630	94	154	136	109	86	123
1730	60	69	40	7	33	44

TABLE II

Half hourly values of q_r ($r = 1, 2, 3, 4$), Q and q.

March 1950—Slough

Hour (L.M.T.)	q_1 cm^{-3}.sec.$^{-1}$	q_2 cm^{-3}.sec.$^{-1}$	q_3 cm^{-3}.sec.$^{-1}$	q_4 cm^{-3}sec.$^{-1}$	$Q \times 10^{-7}$ cm^{-2}.sec.$^{-1}$	q cm^{-3} sec.$^{-1}$
0530	12	18	10	4	11	11
0630	83	87	82	74	64	82
0730	113	160	159	150	96	145
0830	123	200	206	174	134	176
0930	135	196	177	161	142	167
1030	151	188	166	128	120	158
1130	169	179	150	124	106	156
1230	164	184	160	127	102	159
1330	144	181	160	122	108	152
1430	108	160	148	105	111	130
1530	114	175	139	96	109	131
1630	104	158	133	92	93	122
1730	94	160	138	97	90	122
1830	76	122	99	81	76	95

COMPARISON WITH THEORY

For comparison, the values of Q, q and q_r (mean production rate in the rth column) may be calculated from the hypothesis of Bradbury (1938) as follows :

If a gas of constant scale height H is ionized by monochromatic radiation, then the value of $q(h)$, when the solar zenithal angle is χ, is given by the expression due to Chapman (1931).

$$q(h) = q_0 \exp\,(1 - Z - e^{-Z} \sec\,\chi) \qquad \ldots \quad (2)$$

where $Z = \frac{h - h_0}{H}$ and h_0 is the height of maximum production rate q_0 when $\chi = 0$.

According to Bradbury, F_1 and F_2 layers are both produced by the same ionization process. The ionizing radiation for the process, acting on a single ionizable gas constituent, has the height $h(q_m)$ of peak production rate near the level of F_1 layer peak ($h_m F_1$); and, the F_2 layer peak ($h_m\, F_2$) is formed as a result of the rapid decrease of the electron loss coefficient above F_1 layer, the loss coefficient in the F_1 layer being independent of height. The hypothesis of Bradbury is illustrated in Fig 4. According to this hypothesis, when the solar zenith angle is χ, the value of Q, the total electron production in a column of unit cross-section of the F_2 region extending from the "bottom" ($h_o F_2$) to the height of maximum density ($h_m F_2$) is given by

$$Q = \int_{h_o F_2}^{h_m F_2} q(h)\,.\,dh = q_0 H \cos\chi [\exp\,(1 - e^{-Z_2} \sec\chi) - \exp\,(1 - e^{-Z_1} \sec\chi)] \quad \ldots \ (3)$$

$$= q\,.\,T$$

where
$$Z_2 = \frac{h_m F_2 - h_0}{H}$$

$$Z_1 = \frac{h_0 F_2 - h_0}{H}$$

$$T = h_m F_2 - h_0 F_2$$

q = mean production rate in the F_2 layer and q_0 = peak production rate.

The value of the peak production rate (q_0) in the F_1 region when the sun's rays are vertical may be estimated for the quasi-equilibrium conditions (production rate = loss rate) from the expression,

$$q_0 = \frac{\alpha N_m{}^2 F_1}{\cos \chi} \qquad \ldots \quad (4)$$

where $N_m F_1$ = maximum electron density in the F_1 layer when the solar zenithal angle is χ and α = coefficient of recombination in the F_1 layer.

Assuming $\alpha = 5 \times 10^{-9}$ cm^3. sec.$^{-1}$ [Bates and Massey (1946), Rydbeck (1946)], Ratcliffe *et al* found from an analysis of Slough and world-wide data that

$$q_0 \doteq 280\ (1 + 1.4 \times 10^{-2} R)\ \text{cm}^{-3}\ \text{sec.}^{-1} \qquad \ldots \quad (5)$$

where R is the monthly average relative Zürich sunspot number.

It has been suggested (Bates and Massey 1948 and other authors) that the ionizable gas in the F region is atomic oxygen. The value of the scale height (H) of atomic oxygen is about 50 km. between 200 km. and 400 km. according to the R model (based on rocket results) given by Bates (1954). This value of the scale height is consistent with the value (H = 45 km.) accepted by Ratcliffe *et al.* after a critical examination of the experimental results and Bradbury's hypothesis. The value of h_0 accepted by Ratcliffe *et al.* is 180 km. With these values of H and h_0 (45 km. and 180 km. respectively) the hourly values of the total production rate (Q) in the unit column and mean production rate (q) in the F_2 layer have been calculated with the help of Eq (3).

For comparison, the theoretical hourly values of Q and q (calculated on the assumption of Bradbury's hypothesis) and the hourly experimental values (from the mean curves in Fig 5 and Fig. 6) are shown in Table III and Table IV.

To show how the values of the mean production rates $\bar{q}_r$ should fall with increasing order of the sectional column (first column being the lowest one) according to the hypothesis of Bradbury, values of the same have been calculated theoretically. This can be done with the help of the equation

$$q_r = \frac{x}{T}\, q_0 H \cos \chi [\exp (1 - e^{-Z_{2r}} \sec \chi) - \exp (1 - e^{-Z_{1r}} \sec \chi)] \qquad (6)$$

where Z_{2r} = reduced height of the upper boundary of the rth column,

Z_{1r} = reduced height of the lower boundary of the r th column.

TABLE III

Hourly experimental and theoretical values of Q and q.

January 1950—Slough

Hour (L.M.T.)	$Q\times 10^{-7}$ cm^{-2}.sec.$^{-1}$ (Experimental)	$Q\times 10^{-7}$ cm^{-2}.sec.$^{-1}$ (Theoretical)	q cm^{-3}.sec.$^{-1}$ (Experimental)	q cm^{-3}.sec.$^{-1}$ (Theoretical)
09	120	27	220	51
10	144	81	256	133
11	152	94	272	168
12	150	106	260	183
13	140	102	238	170
14	126	85	206	144
15	100	46	168	84

TABLE IV

Hourly experimental and theoretical value of Q and q

March 1950—Slough

Hour (L.M.T.)	$Q\times 10^{-7}$ cm^{-2}.sec.$^{-1}$ (Experimental)	$Q\times 10^{-7}$ cm^{-2}.sec.$^{-1}$ (Theoretical)	q cm^{-3}.sec.$^{-1}$ (Experimental)	q cm^{-3}.sec.$^{-1}$ (Theoretical)
07	80	40	116	61
08	118	101	150	149
09	140	156	162	184
10	132	180	168	212
11	116	128	168	191
12	106	120	164	174
13	104	103	158	178
14	108	157	150	187
15	110	158	138	186
16	104	117	128	146
17	92	67	116	94

Values of the mean production rates of the four sectional columns at midday [1200 hr. (L.M.T.)] so calculated are shown below in Table V for the month of January 1950 and March 1950 at Slough. The calculations were done with values of H, h_0 and q_0 as stated earlier. It is to be noted that $q_1 > q_2 > q_3 > q_4$. This is as it should be, because, as the peak production rate is assumed to be near the F_1 peak height, the mean production rate should decrease with increasing height of the column in the F_2 region.

TABLE V

Theoretical values of q_r ($r = 1, 2, 3, 4$) according to the hypothesis of Bradbury

Hr.—1200 (L.M.T.)—Slough

1950 Month	q_1 $cm^{-3}.sec.^{-1}$	q_2 $cm^{-3}.sec.^{-1}$	q_3 $cm^{-3}.sec.^{-1}$	q_4 $cm^{-3}.sec.^{-1}$
January	201	197	173	166
March	247	206	129	124

DISCUSSION

The computations of the diurnal variations of the mean production rates in the different sections of the F_2 region by the method of analysis, suggested by the author, taking into account the height variation of the attachment coefficient after Ratcliffe *et al.* give consistent results. The diurnal variations are found to be more regular and symmetrical about noon for the winter month (January) than for the equinoxial month (March). The calculated values of the mean production rates for both the months as given in Table I and Table II, show that $q_2 > q_3 > q_4$ for most of the half hourly values. This is in accordance with Table V, except that the experimental q_1's are generally less instead of being greater than q_2's. This may be due to the uncertainty in the correct determination of electron density near the "bottom" of the F_2 region. This uncertainty affects the computed values of n_1. Another possible reason for this discrepancy may be due to the fact that the loss rates in the first column were often calculated from the extrapolated values (below 250 km) of attachment coefficient.

It may be noted from Table III that the theoretical values of Q and q are lower than the experimental values. The difference is smaller for the month of March than for the month of January. It must be mentioned in this connection that the magnitudes of Q and q, calculated theoretically on the assumption of Bradbury's hypothesis, depend on the assumed values of q_0, h_0 and H. The assumed value of q_0, again in its turn, is proportional [Eq. (4)] to the assumed values of the recombination coefficient (α) in the F_1 region. The value of q_0 utilized for the theoretical computation was obtained by Ratcliffe *et al.* by assuming $\alpha = 5 \times 10^{-9}$ cm^3 sec.$^{-1}$. Higher values $\alpha = 8 \times 10^{-9}$ cm^3. sec.$^{-1}$, however, has been suggested (Minnis, 1955). If this latter value is accepted, the theoretically calculated values of q and Q will be increased by about 50% provided the values of H and h_0 are unaltered.

It may thus be concluded that with the height variation of the attachment coefficient suggested by Ratcliffe *et al.* the results as obtained by the method of analysis adopted are consistent with the hypothesis of Bradbury for the formation of the F_2 region.

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REFERENCES

Bates, D. R., 1954, Rocket Exploration of the Upper Atmosphere, Pergamon Press, London, p. 347.

Bates, D. R and Massey, H. S. W., 1946, *Proc. Roy. Soc. A.*, **187**, 261.

Bates, D. R. and Massey H S. W., 1948, *Proc. Roy. Soc A.*, **192**, 1.

Bradbury, N. E , 1938, *Terr. Magn. Atmos. Elect.*, **43**, 55.

Chapman, S , 1931, *Proc. Phys. Soc* , **43**, 26.

Datta, S., 1958, *Indian J. Phys* , **32**, 483

Minnis, C. M., 1955, *J. Atmos. Terr. Phys.* **6**, 91.

Ratcliffe, J. A., Schmerling, E. R., Setty, C. S. G. K. and Thomas, J. O., 1956,*Phil. Trans. A.*, **248**, 621.

Rydbeck, O. E. H., 1946, Chalmers. tek. Hogsk. Handl. No. 53.

Schmerling, E. R. and Thomas, J. O., 1955, Tables of F2 layer Electron Density on International Quiet Days, Cavendish Laboratory, Cambridge, England.

Schmerling, E R. and Thomas, J. O., 1956, *Phil. Trans. A.*, **248**, 609.